TELEVISION WITH CATHODE-RAY TUBES.*

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SUMMARY.

This paper gives a preliminary outline of work with a new, entirely electrical, television system having no moving mechanical parts.

The registration of the image is accomplished by a special device, which is a true electric eye. The device has been named the "iconoscope," and it consists of a vacuum tube containing an electron-emitting gun and a photo-sensitive surface of a unique type. This photo-sensitive surface is scanned by an electron beam from the gun, which serves as a type of inertialess commutator.

A new principle of operation permits the storing of the energy from the light of the image and enormously increases the output as compared with that of conventional types of television scanners.

The sensitivity of the iconoscope, at present, is approximately equal to that of a photographic film operating at the speed of a motion picture camera. The resolution of the iconoscope is high, much higher than is necessary for television of the highest quality.

The reproduction of the image is accomplished by another cathode-ray tube with a fluorescent screen, which has been named the "kinescope." Here the impulses from the transmitter modulate the intensity of the electron beam, and this, in turn, is transformed by the fluorescent screen into variations of light.

The scanning is linear and is synchronized at the end of each line. The synchronizing impulses are transmitted through the same channel as the picture signal.

The whole system is completely automatic and the receiving sets are almost as easy to operate as the ordinary radio receivers.

The paper describes the theory, characteristics, and mode of operation of the system.

INTRODUCTION.

The meaning of seeing over a great distance can be interpreted as sending instantaneously a picture through this distance. This requires means of communication extremely rapid and free from inertia. The discovery of electricity and the development of electrical communication, therefore, laid the foundations for the future realization of television.

The first step towards the conversion of the picture into electrical energy was taken by May in 1873, with his discovery of the photo-resistive property of selenium. Further advance came from Hertz 15 years later through the discovery of the photo-electric effect. The succeeding years witnessed rapid progress as the result of the study of the effect by Hallwachs, Elster and Geitel, and others.

The first proposal of a solution of the television problem by means of the selenium cell was made by Carey in 1875, only 2 years after its discovery. Carey proposed to imitate the human eye by a mosaic consisting of great numbers of minute selenium cells. An actual attempt to construct a mosaic of this kind with a small number of elements was made by Ayrton and Perry in 1877. Later, in 1906, Rignoux and Fournier used a mosaic of this type to transmit simple patterns and letters. Their transmitter consisted of a checkerboard of 64 selenium cells. Each cell was connected by two wires to a corresponding shutter in a similar checkerboard comprising a receiver. The picture was projected upon the selenium cells, creating in them electric currents which, in turn, operated the shutters. The light from behind the shutters reproduced the picture.

Although this idea of separating the picture into small elements, converting the illumination of each element into an electric current, and sending each through a separate wire is a good one, it leads to a very elaborate system. To transmit a picture of good quality, a great many pairs of separate wires would be required, which, of course, is impracticable. To simplify the problem, Nipkow in 1884 proposed, instead of sending all the elements of the picture at once, to transmit the picture point by point, or to scan the picture. This proposal simplified the problem considerably, since it made possible the transmission of the picture over a single wire or over a single communication channel.

The means by which this simplification was achieved was the scanning disc. The introduction of the scanning disc alone, however, did not bring the solution of the problem, owing to the lack of other essential elements. Almost 40 years later, through the development of the thermionic amplifier for radio purposes and the use of gas discharge tubes, television became possible, and various inventors demonstrated television images transmitted by radio.

In the next few years progress was rapid and remarkable results were obtained, considering the difficulties encountered during this period of development. Practically all the work was done by mechanical methods of scanning, using Nipkow discs, polygonal mirrors, mirrored screws, etc. These systems involved purely mechanical complications in the construction of sufficiently precise scanners, difficulties in increasing the number of picture elements, and particularly in obtaining sufficient light. This last limitation actually prevented an increase of the resolution of the transmitted picture sufficient to give the necessary quality, and practically excluded all hope of transmitting an outdoor picture—the real goal of television.

In order to understand fully the reasons for this difficulty we should remember that in all conventional systems of television the picture is scanned point by

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point, and therefore the photo-sensitive element is affected by the light from a given point only for a very short interval of time corresponding to the time of illumination of one picture element. Assume that for a picture of good quality we desire 70 000 picture elements. For 20 repetitions per second, this means that the time of transmission of one picture element is 1/1 400 000 sec. On the other hand, the output of the photo-electric cell, which goes into the amplifier, is proportional to the intensity of the light and to the time during which the light is acting on the cell. A brief computation shows how microscopic will be the output of the photo-electric cell for this number of picture elements. In an average photographic camera with a lens f–1·5, the total light flux falling on the plate from a bright outdoor picture is of the order of $\frac{1}{10}$ lumen. Substituting for the plate a scanning disc suitable for 70 000 picture elements, and using a photo-electric cell with a sensitivity of 10 microamperes per lumen, the photo-electric current from a single picture element will be given by

$$I = \frac{1 \times 10^{-5}}{10 \times 70\,000} = 1{\cdot}43 \times 10^{-11} \text{ amp.}$$

The charge resulting from this current in the time of one picture element is

$$I \times t = \frac{1{\cdot}43 \times 10^{-11}}{1{\cdot}4 \times 10^{6}} = 1 \times 10^{-17} \text{ coulomb}$$

Comparing this with the charge of one electron ($e = 1{\cdot}59 \times 10^{-19}$ coulomb), we see that only 63 electrons are collected during the scanning of one element. The amplification of such small amounts of energy involves practically insurmountable difficulties. If we now compare this condition with that of a photographic plate during exposure, we see that the plate operates under much more favourable conditions, since all its points are affected by the light during the whole time of exposure. This time is several seconds for studio exposures, and of the order of 0·01 second for outdoor exposures, that is, many thousand times greater than for the scanned televised picture. The human eye, which we regard as an ideal of sensitivity, operates also under the same favourable conditions.

If a television system could be devised which would operate on the same principle as the eye, all the points of the picture would affect the photo-sensitive element all the time. Thus in a picture with 70 000 elements the photo-electric output for each point would be 70 000 times greater than in the conventional system. Since scanning is still necessary in order to enable the picture to be transmitted over only one communication channel, we require some means of storing the energy of the picture between two successive scannings of each point.

The Iconoscope.

The author began to work on the realization of this idea some years ago, and devised various solutions of the problem. One of these involved the use of a special cathode-ray tube with a photo-sensitive mosaic structure applied on an insulated metallic plate, as shown in Fig. 1, which is taken from one of the patents already issued upon one form of the development.* Each element of the mosaic is a miniature photo-electric cell. The picture is projected upon this mosaic, resulting in continuous emission of photo-electrons according to the distribution of light in the picture. The charge acquired by each element of the mosaic is released by the cathode-ray beam once in each repetition of the picture. The resulting impulses are amplified and used to modulate the intensity of the cathode-ray beam in the receiving tube, in which the picture is reproduced on a fluorescent screen.

Transmitting tubes of this type were actually built a few years ago, and they proved the soundness of the basic idea. During the succeeding years they were developed in the Research Laboratories of the Westinghouse Electric and Manufacturing Co., East Pittsburgh.

One of the first receptions of a picture with a cathode-ray tube was achieved in 1929, using a mechanical galvanometer for transmitter.† This was reported at the Rochester meeting of the Institute of Radio Engineers in November 1929. The next year the work was moved to the laboratories of the RCA Victor Co., at Camden. Here the development of the cathode-ray receiving system was continued, the pick-up being obtained with a scanning disc. This work has been described in a series of papers published in the *Proceedings* of the Institute of Radio Engineers.

In the meantime the development of the pick-up tube was pushed on, and the results obtained from it soon surpassed those of mechanical scanning, which it eventually completely replaced. The tube itself is called the "iconoscope," from the Greek word "icon," meaning an image, and "scope," signifying observation.

In order to understand fully the operation of the iconoscope, it is best to consider the circuit of a single photo-electric element in the mosaic, as shown in Fig. 2. Here P represents such an element, C being its capacitance to a plate common to all elements, which hereafter will be called the "signal plate." The complete electrical circuit can be traced, from the cathode P_c to C, then to resistance R, source of e.m.f. B, and back to the anode P_a. When light from the projected picture falls on the mosaic each element P_c emits electrons, and thus the condenser element C is positively charged by the light. The magnitude of this charge is a function of the light intensity. When the electron beam which scans the mosaic strikes the particular element P_cC, that element receives electrons from the beam and may be said to become discharged.

The discharge current from each element will be proportional to the positive charge upon the element, and hence the discharge current will be proportional to the light intensity at the particular element under question. The electrical circuit then transforms this discharge current into a voltage signal across the output resistor R.

Let us plot the rise of charge of the element P_cC with respect to time, as shown in Fig. 3. The potential will continuously increase, due to the light of the picture, and the slope of this increase (or dV/dt) will depend

* U.S. Patent No. 1691334. Issued 13th November, 1928; filed 13th July, 1925.

† V. K. Zworykin: "Television with Cathode Ray Tube for Receiver," *Radio Engineering*, 1929, vol. 9, p. 38.

only on the brightness of the particular point of the picture shining on this element. This linearity will be preserved until saturation occurs of the capacitance C, which is so chosen that it will never be reached at a given frequency N of repetition of the discharge. Since the scanning is constant, the interval of time t, which is equal to $1/N$, is also constant, and therefore the value of charge depends only on the brightness of this particular point of the picture. With constant intensity of the scanning beam, the impulse through R—and consequently the voltage drop V_1 across R—is proportional to the brightness of a given point of the picture. This potential V_1 is the output of each single photo-electric element of the ionoscope which is applied to an amplifier.

The above explanation is actually somewhat complicated by the fact that this discharging beam not only neutralizes the positive charge of the photo-electric element, but charges it negatively. The equilibrium potential of the element is defined by (*a*) the velocity of the beam and (*b*) the secondary emission from the photo-emitting substance due to bombardment by the electrons having this velocity. This equilibrium condition, in the dark, for a normal iconoscope, is of the order of 5 to 10 volts negative. The light causes the element to gain a positive charge, thus decreasing the normal negative charge, and the scanning beam brings it back again to the equilibrium potential.

Another complication is due to the existence, besides the discharge impulses, of a charging current of the entire mosaic due to light. This current is constant for the stationary picture, and varies when the picture, or part of it, begins to move across the mosaic. This variation, however, is very slow and does not affect the amplifier, which has a cut-off below 20 cycles per sec.

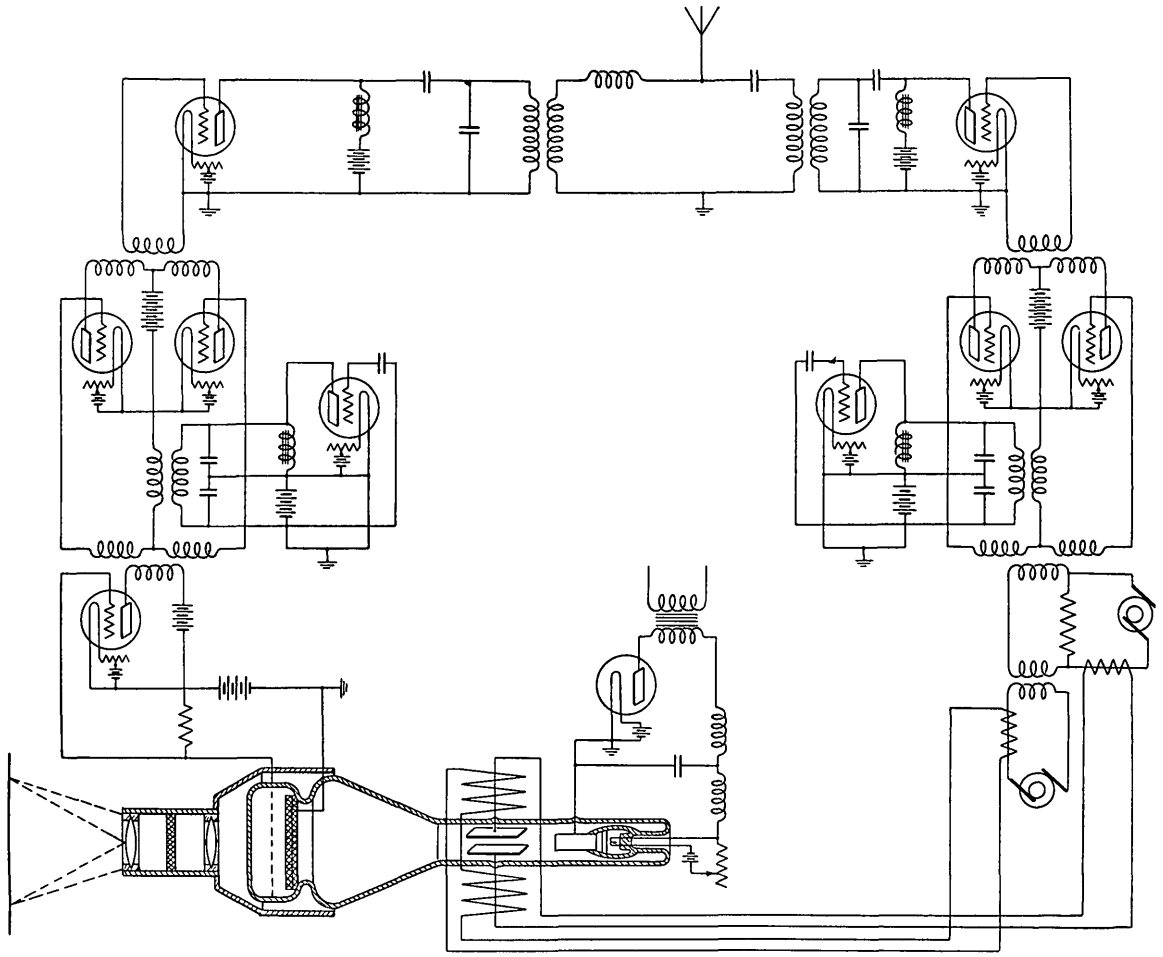


FIG. 1.

In order to compare the magnitude of this output with that of the conventional television system, using a perforated disc, under identical conditions, let us write down the value of the output for the iconoscope and for the usual mechanical method. A typical circuit for mechanical scanning is shown in Fig. 4.

The output of the photo-electric cell, measured across the resistance R, from the disc scanner, is given by

$$V_D = R\frac{F}{n}s$$

where F = luminous flux corresponding to total image; s = sensitivity of photo-electric element; n = number of picture elements; and R = input resistance.

Considering the time necessary to build up the picture signal, we have to satisfy the condition that the time-constant C_2R of the input circuit (C_2 being the capacitance to earth of the photo-electric element and associated circuits) shall be equal to or less than $1/(Nn)$, the time

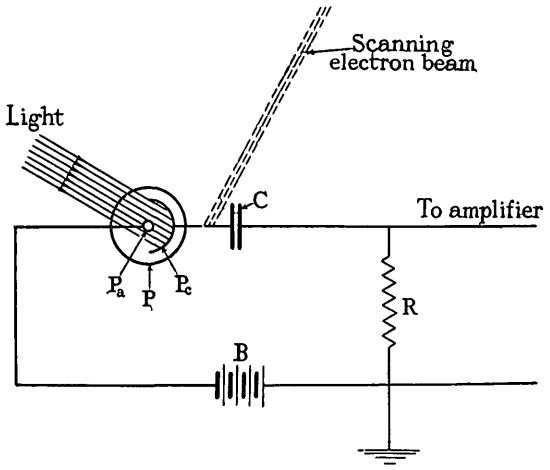


FIG. 2.

of scanning of a picture element (N = number of picture frames per sec.). Thus $C_2R = 1/(Nn)$, from which $R = 1/(NnC_2)$. Introducing this in the expression for the output of the photo-electric cell, we have

$$V_2 = \frac{F}{n}s\frac{1}{NnC_2}$$

which shows that the output decreases as the square of the number of picture elements.

For the charge on one picture element of the iconoscope, we can write approximately

$$Q = \frac{F}{n}st$$

where t, the time during which the light shines on the element, is roughly equal to $1/N$. The output voltage

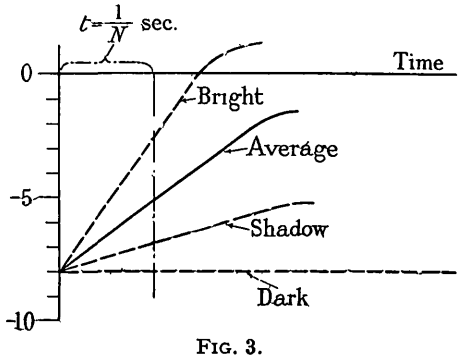


FIG. 3.

from the iconoscope will be $V_1 = Q/C_1$, where C_1 is the total input capacitance to earth of the iconoscope and associated circuits.

Thus

$$V_1 = \frac{Fs}{nNC_1}$$

The ratio between the output from the iconoscope and that from the disc scanner will be

$$\eta = \frac{\frac{Fs}{nNC_1}}{\frac{Fs}{n^2NC_2}} = n\frac{C_1}{C_2}$$

or, for equal output capacitance, $\eta = n$ (the number of picture elements).

If we take the previously-given number of picture elements (n = 70 000), the net theoretical gain of the mosaic system compared with the conventional system of television is 70 000 times. It should be noted, however, that 100 per cent efficiency can hardly ever be attained, but the author has already achieved approximately 10 per cent efficiency, giving a net gain of several thousand times. Such an increase of picture-signal output does not merely serve to decrease the necessary amplification. In the conventional tele-

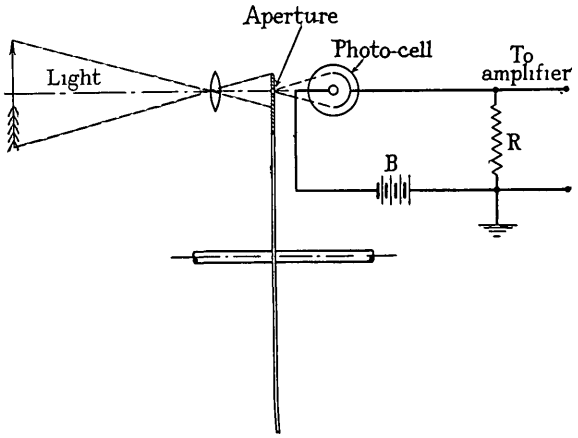


FIG. 4.

vision system the amplification has already been pushed as far as possible from the point of view of permissible noise/picture-signal ratio. This gain, therefore, is the only factor whereby real television can be achieved, if we understand by this term not only the transmission of a picture of limited definition under artificial conditions but also the actual transmission of a picture of high resolution under reasonable or natural conditions of illumination.

The scanning of an object with the flying spot is not considered in this computation, because it represents an entirely artificial condition and cannot be used for television pictures of distant objects.

The schematic diagram of a complete electrical circuit for the iconoscope is shown in Fig. 5. Here the two parts of the photo-electric element P, shown in Fig. 2, are entirely separated. The cathodes are in the shape of a photo-sensitive mosaic on the surface of the signal plate and isolated from it; the anode is common and consists of a silvered portion on the inside of the glass bulb.

The capacitance C of each individual element with respect to the signal plate is determined by the thickness and dielectric constant of the insulating layer between

the elements and the signal plate. The discharge of the positive charge of the individual elements is accomplished by an electron beam originating from the electron gun located opposite the mosaic and inclined at 30° to the normal passing through the middle of the mosaic. Both mosaic and electron gun are enclosed in the same highly-evacuated glass bulb. The inclined position of the gun is merely a compromise in the construction in order to allow the projection of the picture upon the surface of the mosaic.

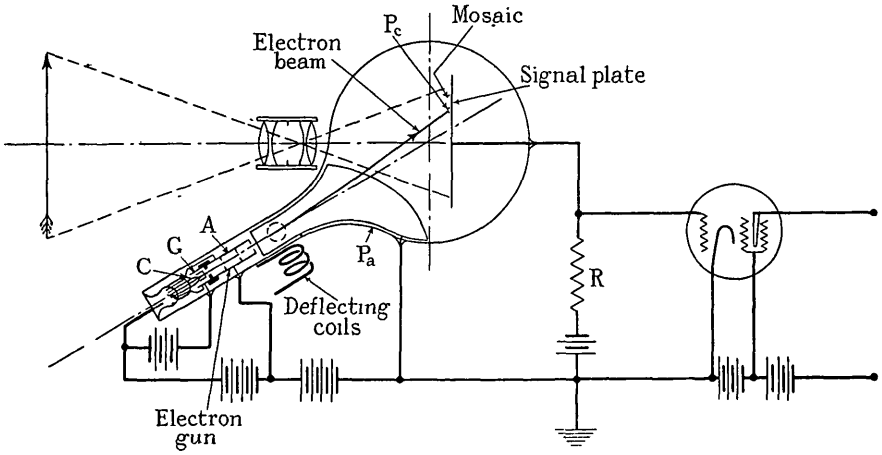


FIG. 5.

The resolution of the iconoscope is determined by both size and number of picture elements in the mosaic and size of the scanning electron beam. In practice, however, the number of individual photo-electric elements in the mosaic is many times greater than the number of picture elements, which is determined entirely by the size of the scanning spot. This is shown diagrammatically in Fig 6. From the initial assumptions formulated in the analysis of the ideal circuit for individual elements, as shown in Fig. 2, we find the qualifications which should satisfy the mosaic for the iconoscope. These assumptions require that all the elements be of equal size and photo-sensitivity and of equal capacitance in respect to the signal plate. The fact that the exploring spot is much larger than the element modifies and simplifies this requirement, so that the average distribution, surface sensitivity, and capacitance, of elements over an area of the mosaic corresponding to the size of the scanning spot should be uniform. This allows considerable tolerance in the dimensions of individual elements.

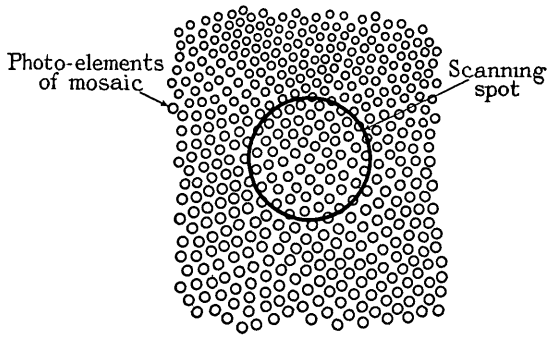


FIG. 6.

The requirement of uniformity, which at first glance is quite difficult to meet, is achieved by the help of natural phenomena. It is known that such a common material as mica can be selected in a thin sheet of practically ideal uniform thickness, and it therefore serves as a perfect insulating material for the mosaic. The signal plate is formed by a metallic coating on one side of the mica sheet. The mosaic itself can be produced by a multitude of methods, the simplest of which is a direct evaporation of the photo-electric metal on to the mica in a vacuum. When the evaporated film is very thin it is not continuous, but consists of a conglomeration of minute spots or globules quite uniformly distributed and isolated from each other. Another possible method is that of ruling the mosaic from a continuous metallic film by means of a ruling machine.

The initial method of formation of the photo-sensitive mosaic was the deposition of a thin film of alkali metal directly on an insulating plate, but subsequent developments in the photo-electric-cell art resulted in changes in the methods of formation of the mosaic.

The mosaic used at present is composed of a very large number of minute silver globules, each of which is photo-sensitized by cæsium through utilization of a special process.

Since the charges are very minute, the insulating property should be as high and the dielectric losses as small as possible. Mica of good quality satisfies this requirement admirably. Other insulators can also be used, however, and thin films made of vitreous enamels have proved to be entirely satisfactory. The insulation should be as thin as it can conveniently be made.

The sensitivity of the mosaic is of the same order as that of corresponding high-vacuum cæsium-oxide photo-electric cells. The same is true also of the colour response. The spectral characteristic is shown in Fig. 7. The cut-off in the blue part of the spectrum is due to the absorption of the glass. The colour sensitivity

of the photo-electric elements is shown as a dotted curve.

The electron gun producing the beam is an important factor in the performance of the iconoscope. Since the resolution is defined by the size of the spot, the gun should be designed to supply exactly the size of spot corresponding to the number of picture elements for which the iconoscope is designed. For 70 000 picture elements and a mosaic plate about 4 in. high, the distance between two successive lines is about 0·016 in., and the radius of the cathode-ray spot approximately half of this size. This imposes a serious problem in gun design.

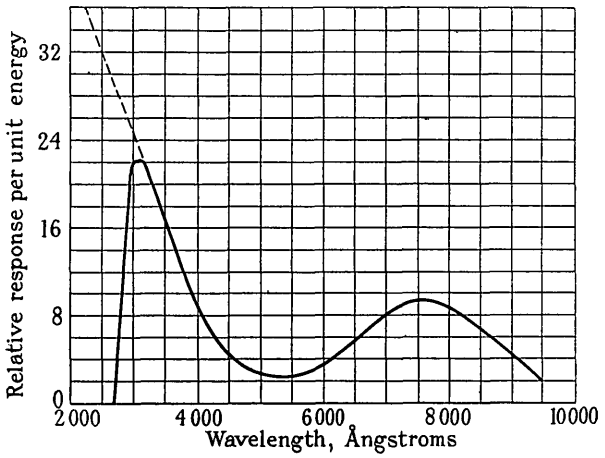


FIG. 7.

The electron gun used for this purpose is similar to the one adopted for the "kinescope," the cathode-ray tube employed for television reception, which has already been described elsewhere.* The components of the gun are shown in Fig. 8. It consists of an indirectly-heated cathode C, with the emitting area located at the tip of the cathode sleeve. The cathode is mounted in front of the aperture O of the controlling element G. The anode A_1 consists of a long cylinder with three apertures aligned on the same axis as the cathode and control element. The gun is mounted in the long, narrow, glass neck attached to the spherical bulb housing the mosaic screen. The inner surface of the neck and of part of the sphere is metallized and serves as the second anode for the gun and also as collector for photo-electrons from the mosaic. The first anode usually operates a fraction of the voltage applied to the second anode, which is approximately 1 000 volts.

The focusing is accomplished by an electrostatic field set up by potential differences applied between elements of the electron gun, the gun itself, and the metallized portion of the neck of the kinescope.

The theory of the electrostatic focusing is described in detail in the author's recent paper.* The lines of force of the electrostatic field, between properly-shaped electrodes, force the electrons of the beam to move toward the axis, overcoming the natural tendency of electrons to repel each other. The action is analogous to the focusing of light rays by means of optical lenses. The electrostatic lenses, however, have a peculiarity in that their index of refraction for electrons is not confined to the boundary between the optical media, as in optics, but varies throughout all the length of the electrostatic field. Also, it is almost impossible to produce a simple, single, electron lens: the field always forms a combination of positive and negative lenses. By proper arrangement of electrodes and potentials, however, it is always possible to produce a complex electrostatic lens which will be equivalent to either a positive or negative optical lens.

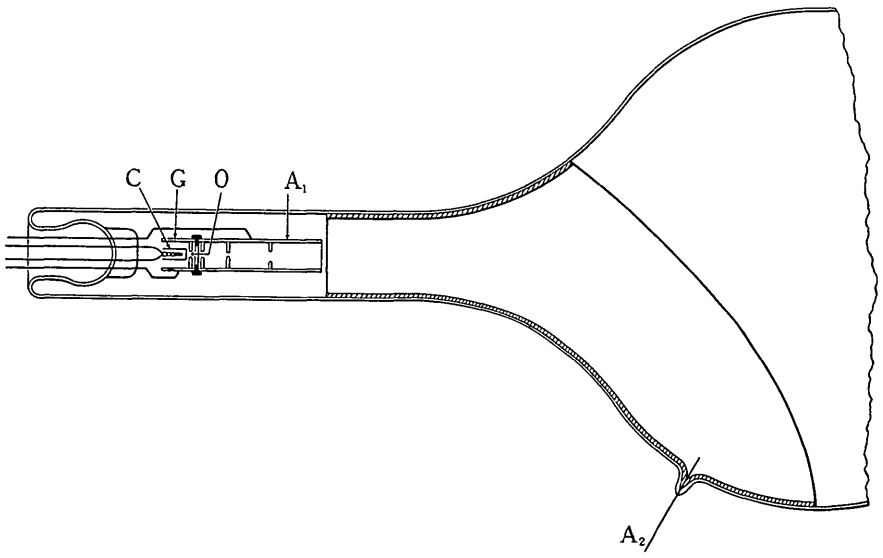


FIG. 8

The distribution of electrostatic fields in the electron gun is shown in Fig. 9. In this particular case, the total action of fields on electrons is approximately equivalent to a combination of four lenses, as is shown in the figure.

* V. K. ZWORYKIN: *loc. cit.*

* V. K. ZWORYKIN: *Journal of the Franklin Institute*, 1933, vol. 215, p. 535.

The first two lenses force the electrons through the aperture of the first anode and ensure the desired control of the beam by the control grid G. The final focusing of the beam on the mosaic is accomplished by the second pair of lenses, created by the field between the end of the gun and the neck of the bulb. Thus, the final size of the spot on the mosaic, as in its optical analogue, depends chiefly on the size of the active area of the cathode and the optical distances between the cathode, lenses, and mosaic.

The velocity of the beam is expressed by the equation $v = 5{\cdot}95 \times 10^7 \sqrt{V_2}$, where v is the beam velocity in cm per sec. and V_2 is the second anode voltage.

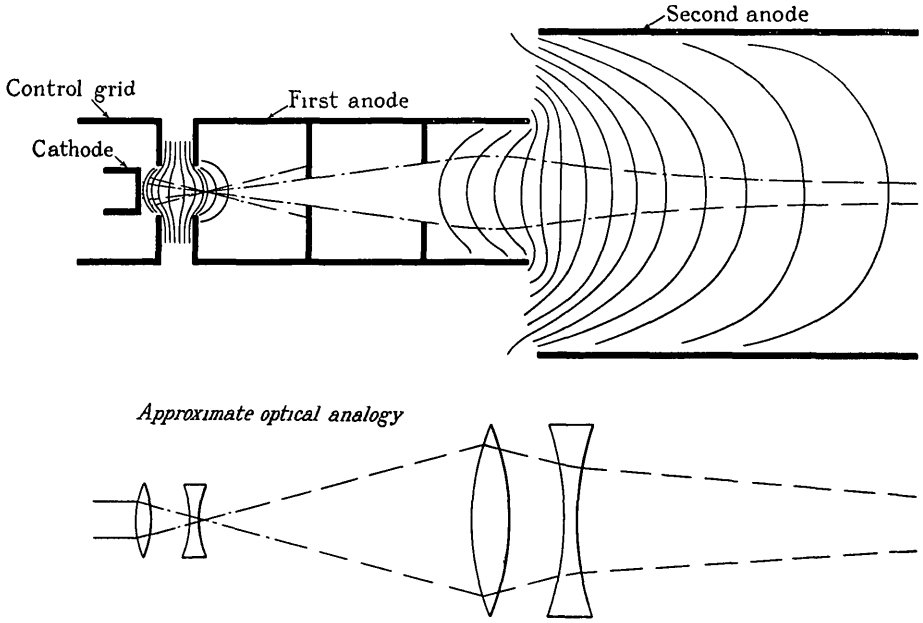


FIG. 9

The appearance of the iconoscope is shown in Fig. 10. The overall length of this particular model is 18 in., and the diameter of the sphere 8 in. The deflection of the electron beam for scanning the mosaic is accomplished by a magnetic field. The deflection coils are arranged in a yoke which slips over the neck of the iconoscope. The assembled deflecting unit is shown

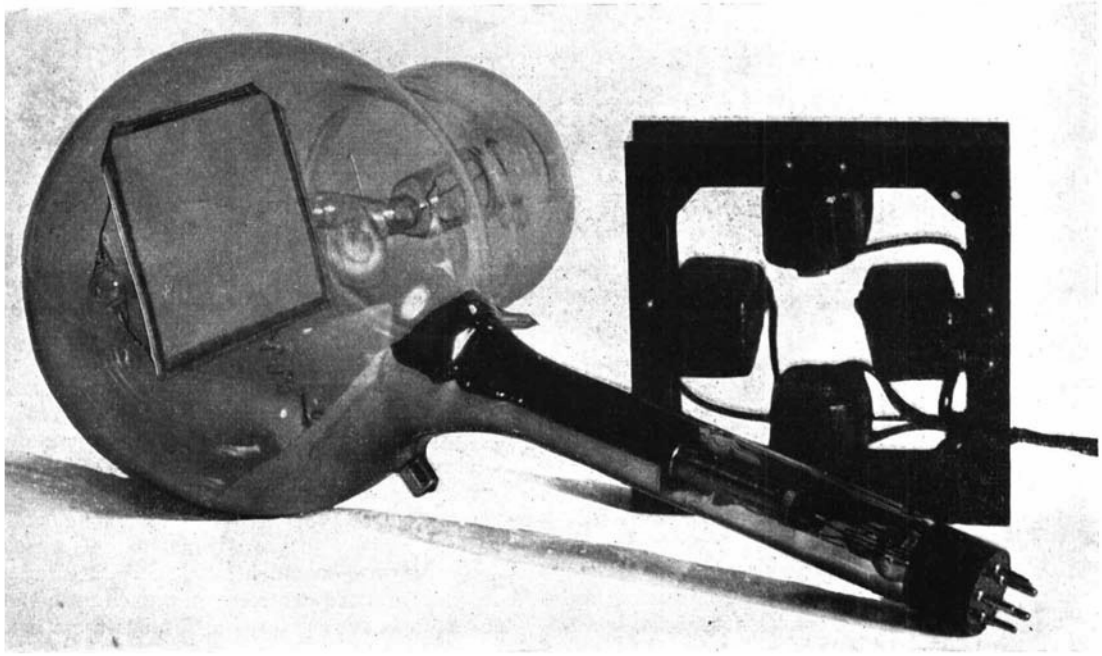


FIG. 10.

beside that of the tube. The scanning is linear in both vertical and horizontal directions, and is caused by saw-tooth-shaped electrical impulses passing through the deflecting coils and generated by special tube generators. The scanning is described in greater detail at the end of the paper.

From the colour response curve shown in Fig. 7 it is clear that the iconoscope can be used not only for transmission of pictures in visual light but also for pictures invisible to the eye, in which the illumination is either by ultra-violet or by infra-red light.

The present sensitivity of the iconoscope is approximately equal to that of a photographic film operating at the speed of a motion picture camera, with the same equipment. The television receiver comprises an antenna system feeding the radio receiver, including the cathode-ray unit or kinescope with its associated horizontal and vertical deflecting equipment.

The main feature of the scheme, as will be seen from Fig. 11, is that in the whole system there are no mechanically moving parts. The transmission of the picture is accomplished entirely by electrical means.

The Kinescope.

The name " kinescope " has been applied to the cathode-ray tube used in the television receiver to distinguish it from ordinary cathode-ray oscilloscopes, from which it differs in several important ways: for

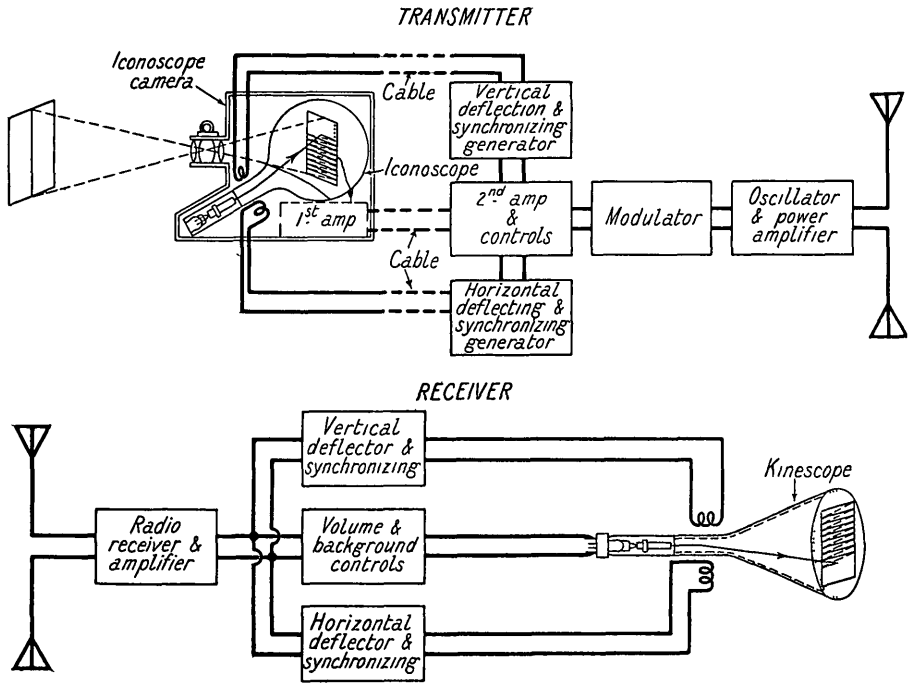


Fig. 11.

optical system. The inherent resolution of the device is higher than that required for 70 000-picture element transmission. Some of the tubes actually constructed are satisfactory up to 500 lines, with a wide margin for future improvement.

Since the iconoscope is practically a self-contained pick-up unit, it is possible to design a very compact camera containing the iconoscope and a pair of amplifier stages connected with the main amplifier and deflecting units by means of a long cable. Since the camera is portable, it can be taken to any point of interest for the transmission of a television picture.

The complete block diagram of the circuit associated with the transmitting and receiving ends of the whole system is shown in Fig. 11, where the components and their location in the system are indicated. Naming the units in order, we have, for television from the studio, the iconoscope camera, the picture-signal and synchronizing-signal amplifiers, the control and switching equipment, and the modulating and radio-transmitter

instance, it has an added element to control the intensity of the beam. Fig. 12 is a cross-section view of one of these tubes (diameter 9 in., reproduced image approximately $5\frac{1}{2}$ in. × $6\frac{1}{2}$ in.), showing the relative position of the elements and the electron gun. The electron gun is similar to the one used for the iconoscope, except that it operates at 4 500 volts for the second anode.

As in the latter, the gun is situated in the long, narrow neck attached to the large cone-shaped end of the kinescope. The inner surface of the cone is silvered or otherwise metallized, and serves as the second anode A_2, the purpose of which is to accelerate the electrons emerging from the electron gun and to form the electrostatic field in such a way as to focus them into a very small, thread-like beam.

After leaving the first anode, the focused, accelerated beam impinges upon the fluorescent screen deposited upon the flat end of the conical portion of the kinescope. The fluorescent screen serves as a transducer, absorbing electrical energy and emitting light. Thus there is

produced a small bright spot on the screen, approximately equal in area to the cross-section of the beam. The fluorescent screen is very thin, and therefore a large portion of the emitted light is transmitted outside the tube as useful illumination.

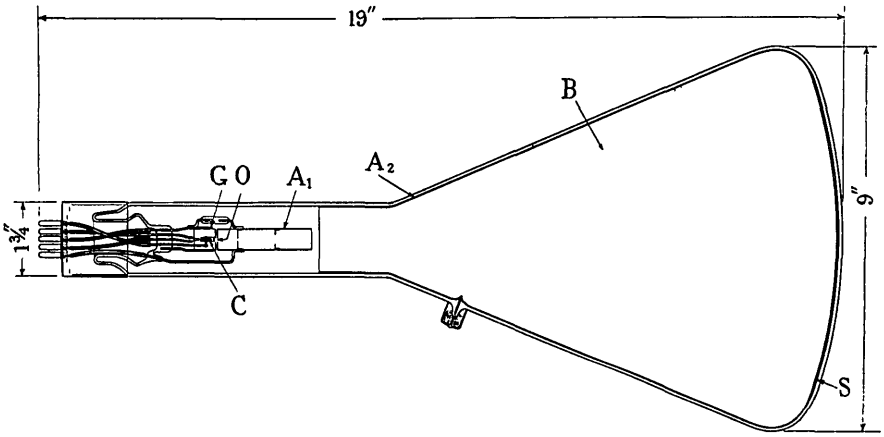


FIG. 12.

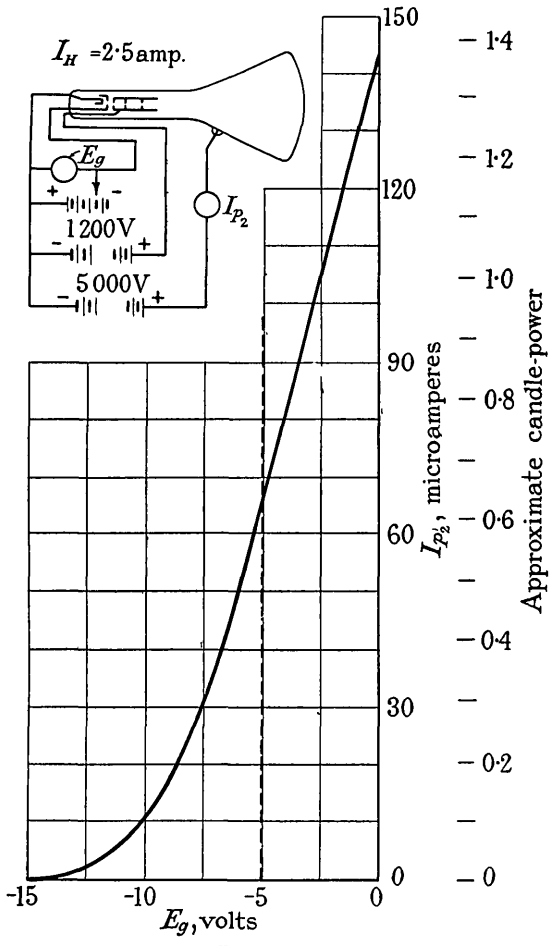


FIG. 13.

In order to reproduce the light-intensity variations of the original picture, it is necessary to vary the intensity of the spot of light upon the fluorescent screen. This is accomplished by means of the control element G of the electron gun. For satisfactory reproduction, the control of the electron-beam intensity should be a linear function of the input signal voltage. Furthermore, it is very essential that during the exercising of this control the sharp focusing of the spot shall not be destroyed. This control should not affect the velocity of the electron beam because the deflection of the beam is inversely proportional to its velocity, and therefore a slight change due to picture modulation would disturb the image, making the bright lines shorter and the darker lines longer. As a result of careful design, the variation of velocity of the beam (from complete cut-off to full brilliance) in the kinescope is so small as to be unnoticeable to the observer of the picture.

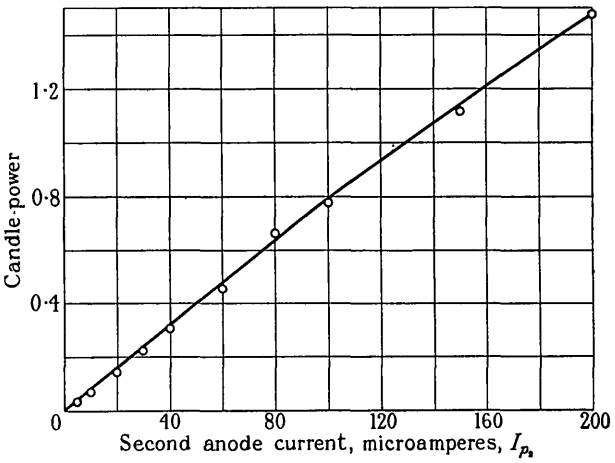


FIG. 14.

The characteristic curve of the kinescope is shown in Fig. 13. From this it will be seen that an a.c. input of 10 volts will give practically complete modulation (i.e. a change from maximum to minimum brilliance) of the cathode-ray beam. The shape of this curve gives the proportionality between input voltage and second-anode current—and corresponding brightness of the spot. (It is to be noted that the values of current, voltage, illu-

mination, etc., given in Fig. 13, and all other figures in this paper, are illustrative rather than specific values for a particular type of cathode-ray kinescope tube.)

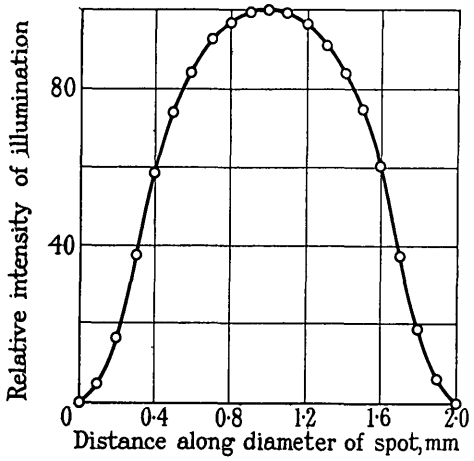


FIG. 15.

By referring to Fig. 13, which shows the relation of second-anode current to the light emitted from the fluorescent screen, it will be noticed that a linear proportionality exists. We can therefore draw the conclusion that a television picture, varying in shade from black to white, will have accurately reproduced all the intermediate shadings necessary for good half-tone pictures.

If we inspect the fluorescent spot by means of an enlarged photograph, we find that the light intensity is not uniform. When measured for a stationary spot, enlarged 50 times, the curve obtained from densitometer observations (see Fig. 15) shows that the light intensity increases toward the centre of the spot. The actual diameter of the spot was 2 mm. During the scanning of a picture, when the spot is in motion, the light intensity per unit area of screen decreases proportionately to the scanned area. The edges of the spot, being less luminous, therefore disappear and the apparent size of the spot decreases. This explains the fact that the diameter of the static spot is larger than the value calculated by dividing the picture height by the number of scanning lines. The photograph of the spot also shows why black spaces between the scanning lines of the received picture may be noticed upon close observation. This effect is caused by the differences in light intensity between the centre and the edges of the spot.

The material used for the fluorescent screen is a synthetic zinc orthosilicate phosphor almost identical with natural willemite. Zinc orthosilicate phosphor was chosen because of its luminous efficiency, its short time-lag, its comparative stability, and its resistance to " burning " by the electron beam. The good luminous efficiency is due to the fact that the light, green in colour, emitted by the zinc orthosilicate phosphor lies in the visible spectrum in a narrow band peaked at 5 230 Å, close to the wavelength of maximum sensitivity of the eye (5 560 Å) as shown in Fig. 16. The luminous efficiency

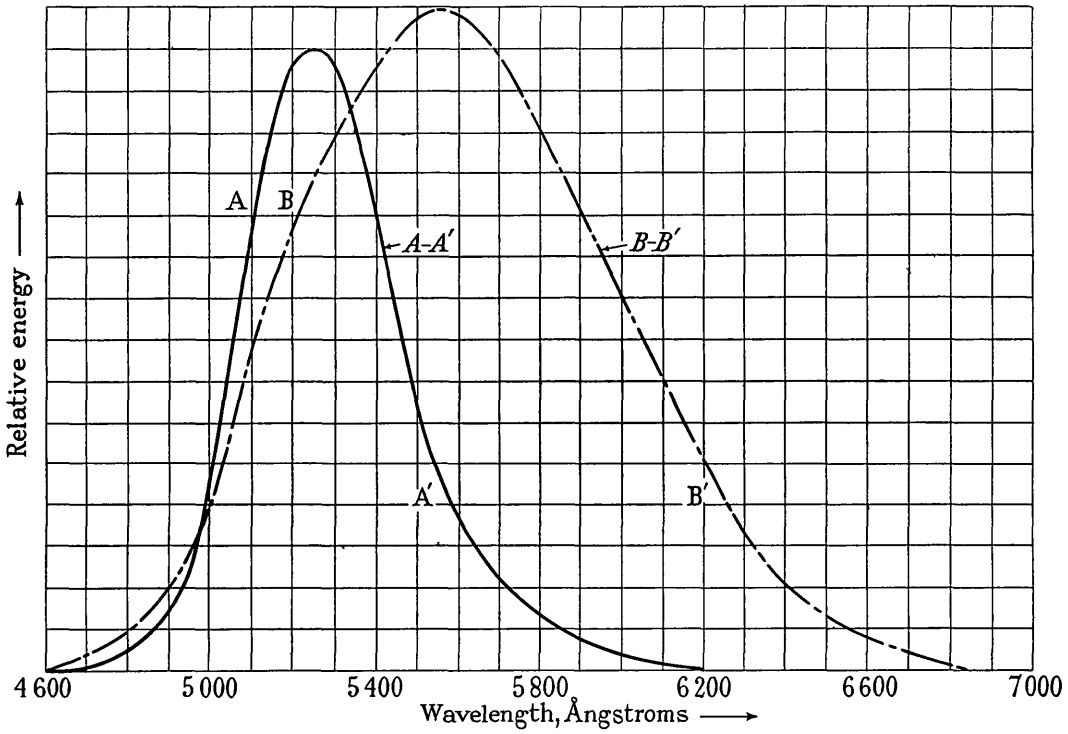


FIG. 16.—Spectral distribution curves.

A–A′ = Spectral distribution of zinc orthosilicate phosphor.
B–B′ = Spectral sensitivity curve of the human eye.
NOTE.—The band maximum in each case is not related to the other maxima.

of incandescent tungsten lamps ranges from 2·5 to 4·0 per cent,* whereas the zinc orthosilicate phosphor has an efficiency of 1·8 to 2·7 per cent when expressed on the basis of lumens per watt, assuming 690 lumens per watt as the maximum theoretical efficiency.† Fig. 17

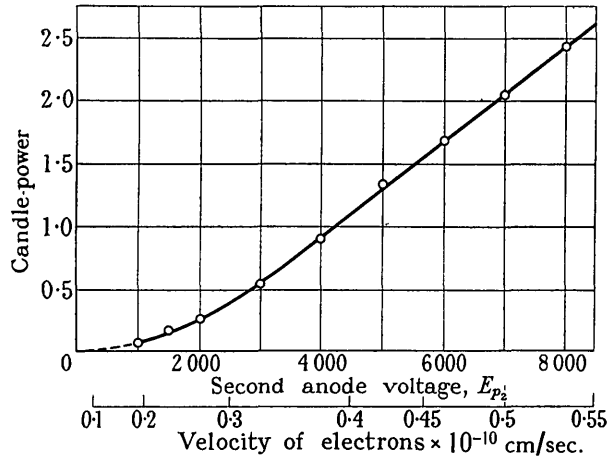


FIG. 17.

shows candle-power plotted against second anode voltage, and Fig. 14 shows candle-power plotted against current carried by the electron beam for the cathode-excitation of zinc orthosilicate phosphor. The general relation between candle-power, applied voltage, and current intensity, for phosphors excited by cathode rays, is:—

Candle-power of emitted light = $AI(V - V_0)$‡

where A = a constant characteristic of the phosphor;
I = current density in the beam, in amperes per cm^2;
V = applied voltage, in volts;
and V_0 = extrapolated minimum exciting voltage, in volts (a constant for each phosphor).

Fig. 18 shows the time/decay curve of the zinc-orthosilicate-phosphor luminescence. The decay curve shows that at the end of approximately 0·06 sec. practically all visible luminescence has ceased. For reproducing 20 pictures per second, the decay curve of the ideal phosphor should be such that the phosphor just loses its effective brilliance at the end of $\frac{1}{20}$ sec. If the time of decay is too long, the moving portions of the picture will "trail": for instance, the path of a moving baseball will appear to be marked by a comet-like tail. If the time of decay is too short, flicker will be noticeable because of the space of comparative total darkness between the times when the fluorescent material is excited by successive pictures.

When the electron beam strikes the fluorescent screen, the latter acquires a negative charge, which, because of the good dielectric properties of the phosphor, remains on the surface and acts as a repulsive force upon the electron beam. It may even completely repulse the beam from the screen, thus stopping the light emission. To remove this charge, the author at first employed a half-transparent, metallic film placed between the end of the kinescope tube and the fluorescent screen. Later, it was found that a properly-prepared phosphor emits a sufficient ratio of secondary to primary electrons to remove the accumulated charges. The secondary electrons are attracted to the high, positively-charged metallized inner surface of the kinescope, and thus the negative charge is carried away. Consequently the kinescopes used in this equipment do not have a transparent metallic film under the fluorescent screen.

The advantages of the kinescope over other means for reassembling the picture at the receiver are: the use of an inertialess beam, easily deflected and synchronized at speeds far greater than those required for television; a sufficiently brilliant fluorescent spot, which may be viewed directly on the end of the tube, thus eliminating the restricted viewing angle usually associated with mechanical scanners; noiseless operation; and the outstanding feature of the flexibility of the cathode-ray tube itself.

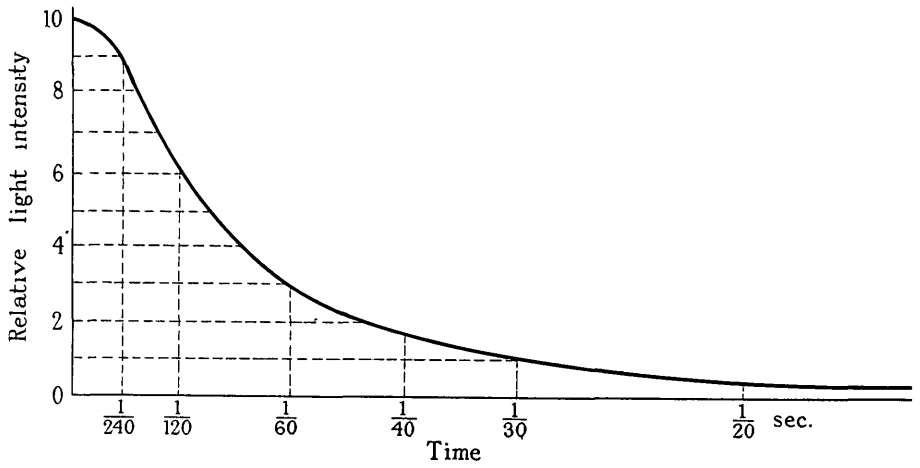


FIG. 18.

A relative light intensity of 10 corresponds to fluorescence during excitation.

* W. E. FORSYTHE and E. M. WATSON: *Journal of the Franklin Institute*, 1932, vol. 213, p. 623.
† A. SCHLOEMER: "The Cathode-ray Oscillograph and Phosphorescent Material," *Zeitschrift für Technische Physik*, 1932, vol. 13, p. 243.
‡ WIEN-HARMS: "Handbuch der Experimental physik," vol. 23, part 1, p. 168.

Scanning.

The problem of picture transmission is essentially 3-dimensional, two dimensions being required for expression of area, while a third is required to indicate intensity. Since a single radio channel is ordinarily capable of transmitting only 2-dimensional intelligence, namely intensity of signal and duration of time, it is evident that the concept of area in a picture must somehow be effectively reduced to a succession of unidimensional signals. This requirement introduces the necessity of scanning: that is, exploring the picture area, element by element, in some logical order in an interval of time so brief as not to be detectable by the human eye, owing to its persistence of vision.

One of the simplest methods of scanning a picture is to cause a spot of light to sweep across it in a succession of parallel horizontal lines. The motion of the spot across the picture may be either unidirectional or sinusoidal. An example of the latter type of scanning was employed with motion-picture film in the system described in an earlier paper.* At the transmitter this was accomplished by means of a galvanometer mirror which reflected the scanning beam on to the continuously-moving film. In the cathode-ray receiver this kind of motion is easily duplicated by deflecting the beam by a magnetic field produced by a sinusoidal current identical with the one energizing the galvanometer. This system has been superseded by unidirectional scanning. An example of unidirectional motion in scanning is that produced by the Nipkow disc, which is widely used in television.

In the present system the scanning is also unidirectional and is accomplished by deflecting the electron beams of both the iconoscope and the kinescope by means of electromagnetic fields. The beam traces a succession of equally-spaced horizontal lines across the fluorescent screen, constructing the television picture in the identical manner that the flying spot at the disc transmitter has scanned it, beginning from the top downward, and after the last line jumping back to the position at the start of a new picture.

In order to scan with a cathode-ray beam in this manner, two variable magnetic fields are applied to the beam just as it emerges from the electron gun; a vertical field, pulsating N times per second, and a horizontal field, pulsating as many times faster as the number of lines in the picture.

When an electron beam passes through a magnetic field it is deflected in a direction normal to the magnetic lines of force according to the well-known equation*

$$\delta_1 = \frac{evH}{2m}\frac{l^2}{v^2}$$

where δ_1 = displacement from the initial straight path; e = charge on the electron; m = mass of the electron; H = intensity of magnetic field; l = length of path in magnetic field; and v = velocity of electron; all the quantities being expressed in electromagnetic and C.G.S. units.

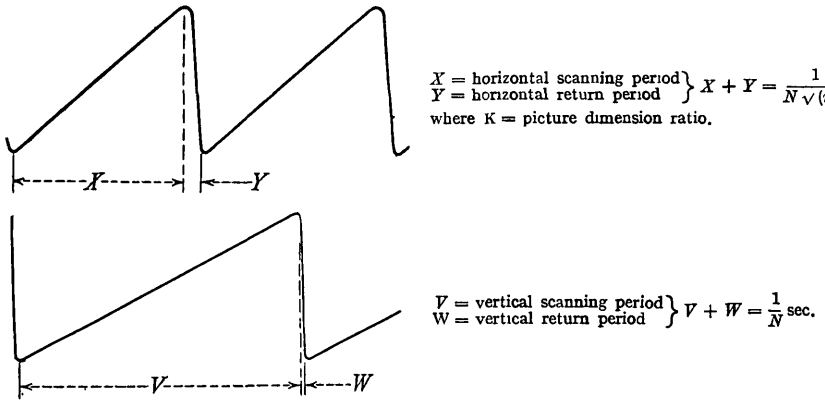
The further displacement, during the time necessary to traverse the path from the magnetic field to the screen, is equal to $evHlL/(mv^2)$. The total displacement is given (in cm) by

$$S = \delta_1 + \delta_2 = \frac{e}{m}\frac{Hl}{v}\left(\frac{l}{2} + L\right)$$

where L is the distance from the deflecting magnetic field to the fluorescent screen.

In order that the cathode beam at the receiver may follow the unidirectional scanning at the transmitter, the variation of intensity of both horizontal and vertical deflecting fields plotted against time is of a " saw-tooth " shape, as shown in Fig. 19. Each cycle consists of two parts: the first, linear with respect to time and lasting practically the whole cycle; and the second, or return period, lasting only a small fraction of the cycle. The picture is reproduced during the first part of the scanning period by varying the bias of the control element according to the light intensities of the transmitted picture, as described above.

There are a number of methods that will produce " saw-tooth "-shaped electrical impulses. A simple one, which has been described in an earlier paper,† consists in charging a condenser through a current-limiting device such as a saturated 2-electrode vacuum valve and then



X = horizontal scanning period, Y = horizontal return period $\Big\}$ $X + Y = \frac{1}{N\sqrt{(nK)}}$ sec.
where K = picture dimension ratio.

V = vertical scanning period, W = vertical return period $\Big\}$ $V + W = \frac{1}{N}$ sec.

FIG. 19.

* V. K. ZWORYKIN: " Television with Cathode Ray Tube for Receiver," *Radio Engineering*, 1929, vol. 9, p. 38.

* J. T. IRWIN. " Oscillographs " (Pitmans, 1925).

† V. K. ZWORYKIN: *loc. cit.*

discharging the condenser through a thermionic or gas-discharge tube. The practical limitation of this " saw-tooth " generator lies in the fact that there is no such thing as a completely-saturated thermionic valve. Therefore, the condenser cannot be charged exactly linearly with time, and consequently the line reproduced on the fluorescent screen will be not exactly straight.

In order to straighten the scanning lines and improve the quality of the reproduced picture, a more complicated circuit has been used, involving one dynatron oscillator and two amplifying tubes, as shown in Fig. 20. The condenser C in the horizontal deflecting circuit is charged continuously through the resistance R. Periodically, at the end of predetermined intervals, the condenser is discharged. During these intervals the accumulated charge means of magnetic fields generated by coils placed about the neck of the cathode-ray tube.

The choice of magnetic in preference to electrostatic deflection was made more as a result of economical considerations than of mechanical choice. The kinescope for electromagnetic deflection is much cheaper to make than one equipped with inside deflecting plates for electrostatic deflection. On the other hand, the electromagnetic deflecting unit itself requires more power and is more costly to build than the electrostatic one. The predominance of one or more factors depends chiefly upon the frequency of deflection and velocity of the beam.

The constants of the electrical circuits for vertical and horizontal deflection are, of course, entirely different,

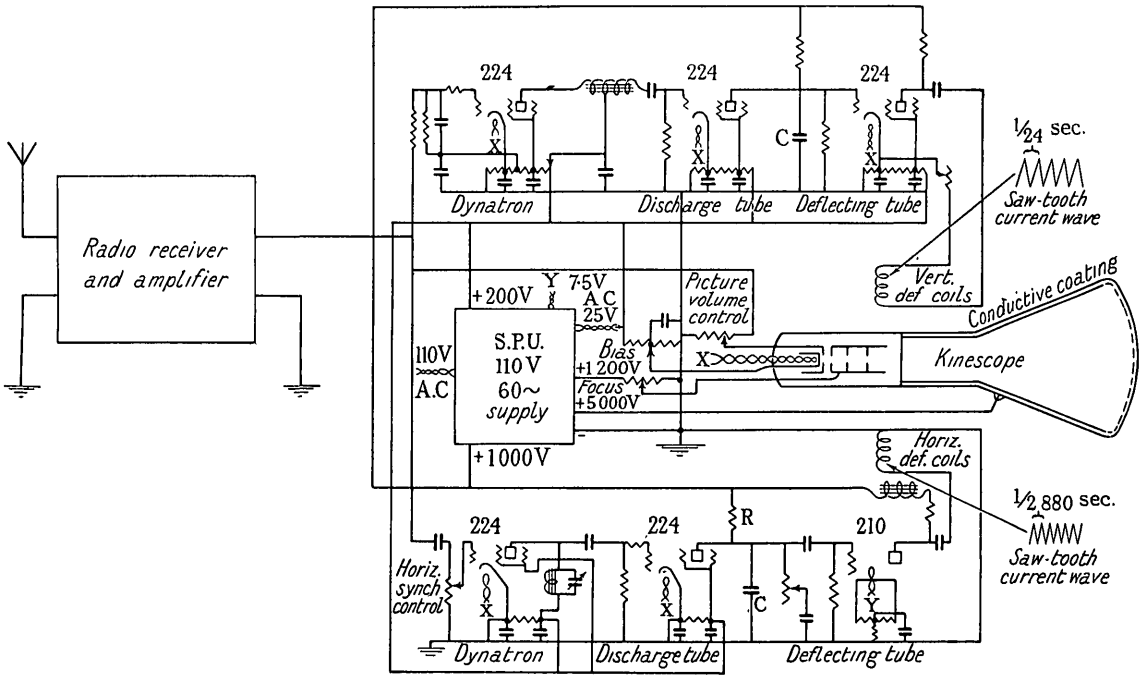


FIG. 20.

does not reach saturation value, for the time is insufficient. The vacuum tube through which the discharge takes place is controlled by impulses supplied from a dynatron oscillator having a distorted wave-shape. The frequency of oscillation of the dynatron (which can be made to vary over a fairly wide range) is initially adjusted approximately to the frequency of the scanning of the transmitter, so that received synchronizing signals will have no difficulty in pulling the dynatron into step with the synchronizing impulses generated by the transmitter scanning disc, as explained later. The processes of charging and discharging condenser C represent saw-tooth variations of potential, which, when applied to the grid of an amplifying tube, produce saw-tooth current impulses in deflecting coils connected in the plate of the amplifier.

The vertical deflecting circuit is similar to the horizontal circuit just described. The vertical and horizontal deflecting systems both operate on the beam by owing to the great difference in the operating frequencies of the two deflection circuits.

SYNCHRONIZATION.

When both deflecting circuits are properly adjusted and synchronized with the transmitter, a pattern consisting of a number of parallel lines is seen on the fluorescent screen. The sharpness of the pattern and perfection of its synchronization with the iconoscope determine to a large extent the quality of the reproduced picture. This pattern is transformed into the picture by applying the picture-signal impulses from the transmitter to the control element of the kinescope, so as to vary momentarily the brilliance of the spot.

For sending synchronizing signals to the receiver, the impulses produced by the deflecting generators of the iconoscope are fed into the amplifier and united with the picture signals, and are therefore transmitted over the picture-signal channel. They do not interfere with the

picture signals, because they occur at an instant when the picture is not being transmitted.

Vertical synchronization is carried out in the same manner, synchronizing impulses for this purpose being transmitted at the completion of each frame.

Considerable advantage is gained from using a synchronizing system in which the beam at the receiver is brought into step with the transmitter at the end of each horizontal line, because under these conditions momentary disturbances of the nature of static do not appreciably affect the picture.

It will be seen that the radio transmitter is modulated by picture signals, horizontal synchronizing signals, and vertical synchronizing signals. The resulting composite signal which is fed to the receiver's modulator grid therefore appears as shown in Fig. 21, the top curve of which represents the irregular-shaped picture signals, which are often unsymmetrical about the axis, usually being more positive than negative. Both synchronizing signals are arranged to have their peaks on the negative side of the axis. The difference in shape of the horizontal and vertical impulses, of course, is due to the time of duration of both signals, and the resultant difference in wave-shape is utilized at the receiver for the purpose of separating these two synchronizing impulses. The three signals mentioned above differ in frequency and in amplitude. The peak picture-signal amplitude is carefully adjusted so as to be always less than the horizontal and vertical impulses, the amplitude of the latter being approximately equal.

The separation of the three signals at the receiver is accomplished by a very simple means which will be described in detail elsewhere; only the fundamentals will be mentioned here. If we trace the signals at the receiver from the antenna through the radio receiver and amplifier, shown in Fig. 20, we find that they are applied to three independent units—the vertical deflecting system, the horizontal deflecting system, and the input to the kinescope. The synchronizing impulses do not affect the picture on the kinescope because they are transmitted at a time when the cathode-ray beam is extinguished, that is, during its return period. The picture signals do not affect the deflecting circuits because amplitude selection is utilized: that is, the amplitude of the picture signals is never sufficient to affect the input of either deflecting system. The selection between vertical and horizontal synchronizing impulses is made on the basis of wave-shape selection. A simple filter in each of the input circuits of the two deflecting units gives satisfactory discrimination against undesired synchronizing impulses. The plate circuits of both dynatron input tubes contain circuits approximately resonant to the operating periods of their respective deflecting circuits, thus aiding in the matter of selectivity.

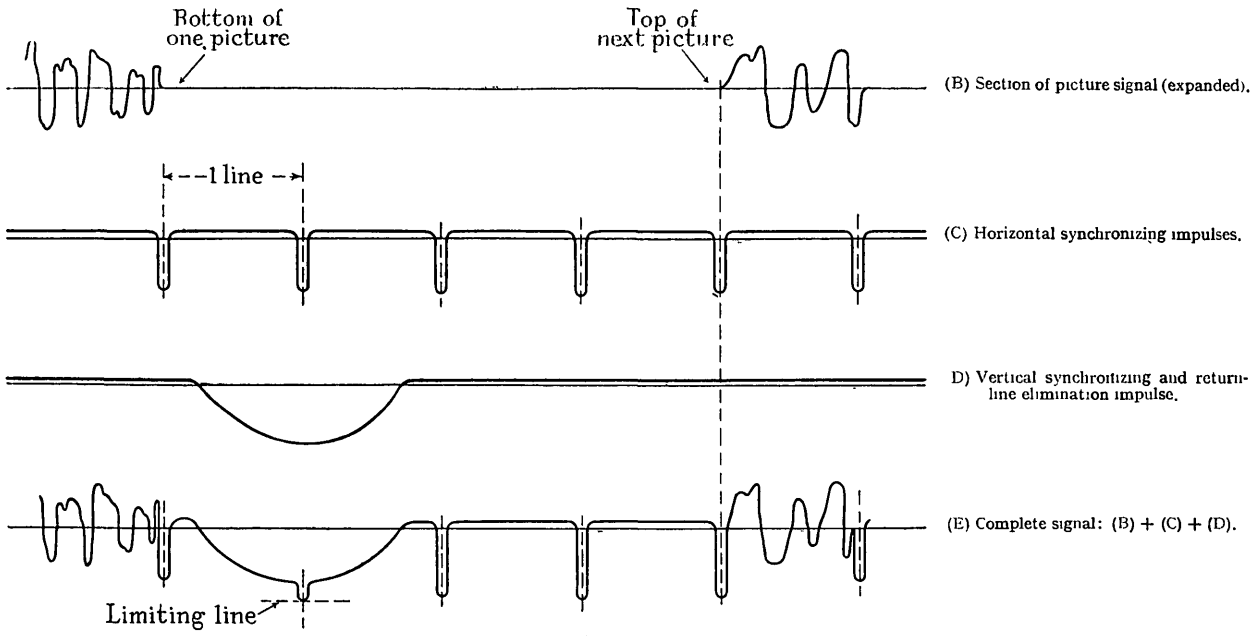

Bottom of one picture
Top of next picture
(B) Section of picture signal (expanded).
1 line
(C) Horizontal synchronizing impulses.
D) Vertical synchronizing and return-line elimination impulse.
(E) Complete signal: (B) + (C) + (D).
Limiting line

FIG 21.

When the electron beam returns to the position from which it starts to trace a new line, and particularly when it returns from the bottom of the picture to start a new frame, an undesirable light trace, called the return line, is visible in the picture. In order to eliminate this, the synchronizing impulses which are in the negative direction are applied to the control electrode of the kinescope, so as to bias it negatively and thus eliminate the return line by extinguishing the beam during its return.

To produce a picture, the intensity of light on a fluorescent screen is varied by impressing the picture signal on the kinescope control element. If the bias adjustment in the kinescope is set so that the picture signals have the maximum swing on the characteristic curve of the kinescope (shown in Fig. 13), a picture with optimum contrast is produced. The operator can control the picture background, or the average illumination of the picture, by adjusting the kinescope bias.

Reproducing Equipment.

The arrangement of the television receiver built for these tests is shown in Fig. 22, which is a photograph of

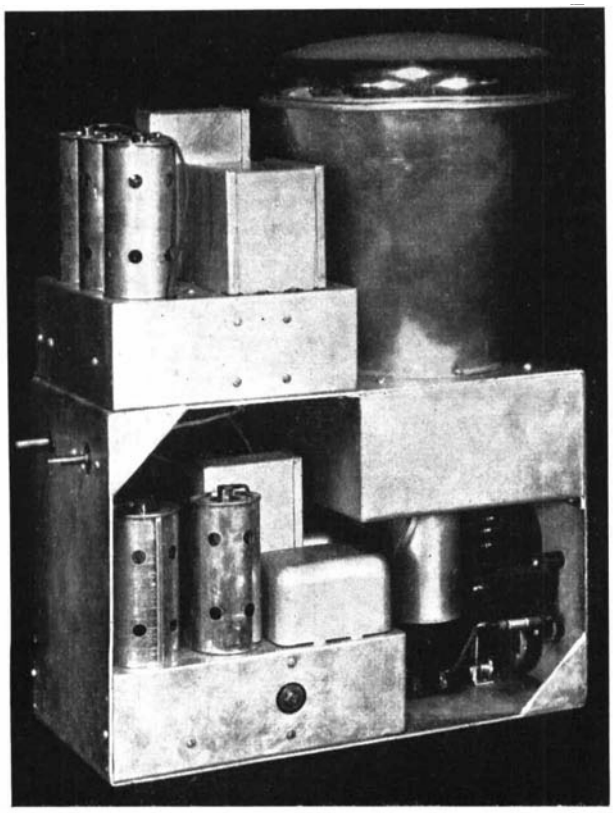


Fig. 22.

the chassis containing the deflecting unit and kinescope. This chassis slides as a unit into the cabinet. The complete receiver contains a power unit, a kinescope unit, two radio receivers (one for picture and one for sound signals), and a loud-speaker.

The reproduced image is viewed in a mirror mounted on the inside lid of the cabinet. The lid shields the picture from overhead illumination and affords a greater and more convenient viewing angle. The brilliance of the picture is sufficient to permit observation without the necessity of completely darkening the room. Since this type of television receiver has no moving mechanical parts it is quiet in operation.

The following operations have to be performed in tuning such a receiver. After the power switch has been turned on, the picture and sound receivers are tuned to their respective signals in the ordinary manner. Next, the picture " volume " control (radio sensitivity control) is adjusted until the point is reached at which the picture locks into synchronism. Then the signal voltage (picture-frequency amplification) to the kinescope is adjusted to the best operating point determined by observation. The background control is adjusted to the desired value, depending upon the type of picture being transmitted.

With the advent of an instrument of these capabilities, new prospects are opened out for high-grade television transmission. In addition, wide possibilities appear in the application of such tubes in many fields as a substitute for the human eye, or for the observation of phenomena at present completely hidden from the eye. Thus they could be used in conjunction with the ultraviolet microscope.

The author wishes gratefully to acknowledge the untiring and conscientious assistance of Messrs. G. N. Ogloblinsky, S. F. Essig, H. Iams, A. W. Vance, and L. E. Flory, who carried out much of the experimental work connected with the development described in the paper, and whose ability was the major factor in the successful solution of the many problems which arose in the course of the investigation.